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Mechanical Engineering and Materials Science Independent Study

Mechanical Engineering & Materials Science

5-2-2018

# Artery tortuosity measurements through MRI image analysis

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Independent Study Report
05/09/18

## Abstract

MATLAB script was written interpreting MRI scans of mouse arteries. This was done in order to acquire tortuosity values, defined as actual length divided by geometric length, which involved calculating centroids based off of planes perpendicular to the outer wall, and summing distances between successive points to calculate the actual length. On average, tortuosity values were found to be 2.34 (for 10 mice), which was a bit high. The script provided a graphical representation of the artery along with calculated centroids, and this was used to assess the accuracy of results. A late discovery of the resolution dimensions used to acquire the initial data meant that all calculations were slightly off; the z-axis was twice as compressed as expected. The code will yield lower tortuosity values once this is fixed.

## Introduction

Tortuosity is the quantification of how convoluted an artery's path is between two points of interest. Specifically, tortuosity can be defined as the actual length (AL) of an artery divided by the geometric length (GL), the Cartesian distance between the segment start and end points as shown in Fig. 1 [1].

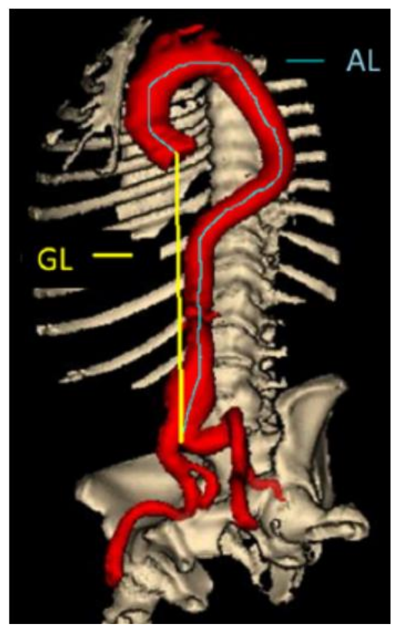


**Fig. 1 Aortic tortuosity in a Marfan patient, as measured by the ratio of actual length (AL) to geometric length (GL). From Franken et al. [1]**

Certain connective tissue disorders (CTD) such as Marfan syndrome are correlated with higher tortuosity values, as Fig. 1 hints at through the roundabout artery path. CTDs are most dangerous by their association with thoracic ascending aneurysms (TAA), and as such, reports have recently investigated and suggested tortuosity may be an indicator of TAA progression [2].

Currently, almost 60% of patients experience aortic dissection before meeting the standard criterion for surgery [3]. This is partly because intervention guidelines only take into account artery diameter and growth rates, whereas the mechanics of the artery are both much more complex and phenotype dependent [4]. Tortuosity measurements might yield more accurate prediction models for TAA and CTDs in the future.

Mouse models of CTD were used for their benefit of prospective studies and well controlled variables. Non-invasive MRI imaging was used to collect data of the mouse arteries, under the form of chains of two-dimensional images. The non-invasive aspect of MRI imaging has the advantage of allowing continued studies of the same mouse, which enables acquisition of time-dependent data and the prospect of tracking the effectiveness of various TAA treating drugs over time.

The main purpose of this study was to develop MATLAB script to interpret Dr. Wagenseil's lab's previously acquired MRI data and to yield tortuosity values.

**Procedure**

The lab did previous work marking up MRI pictures to label regions in which parts of the artery were visible (there were between 140 and 160 pictures for each artery which corresponded to different artery layers). These files constituted the most raw form of data used in the study.

Artery files were imported into the VOXA program, which yielded volume structures in the form of large three-dimensional logical matrices. These matrices display "1" if the associated pixel was marked as an artery component, and "0" if not. The first task of the MATLAB script was to transform the three-dimensional matrices into a more manageable form, specifically a {n x 3} matrix in which n is the number of points where the artery was found to exist, and the columns contain the x, y, and z coordinates of these points. It is worth noting that at this point these coordinates were integers. The script then graphed these points into a cloud of scatter points, which were later used to check the accuracy of the code, as well as to provide a good visual while developing the script.

Using premade MATLAB functions, the script found the centroids and diameters of artery slices parallel to the x-y plane (where the layer level is equivalent to the z coordinate). This yielded an intermediate set of centroids that were inaccurate at points, but still useful for computing actual centroids from planes normal to the outer wall. The imperfections of this first method are displayed in Fig. 2 in the arch. From the temporary z-axis based centroids, a set of outer wall points were found and stored in a matrix in order of procession from the bottom of the artery to the tip closest to the heart.

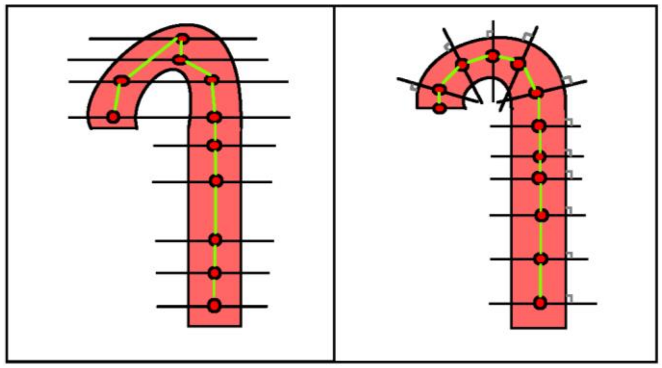

**Fig. 2 Finding centroids from z-axis cuts (left) versus finding centroids on planes perpendicular to outer wall**

The outer wall points were treated as reference points in a plane defined by the normal vector linking successive points within the matrix (with the final plane being defined by the vector: < 0, 0, -1 >). A unit vector named "unitDef" was found for the whole volume that roughly lined up with the x-y plane orientation of the artery. This vector was used to create a line originating from the outer points and traveling inward, where the z values were calculated from the plane equation and the desired x-y search direction. Once the line traversed the entire artery, points were found diametrically opposite to the outer wall ones, and the centroids were defined as the middles of those segments.

Reiterating the previous steps in various directions and averaging the centroids found each way improved accuracy of the script. Furthermore, data was smoothed at different steps of the procedure, first to account for the low resolution of the initial data, and second to improve the averaging process mentioned above.

Lastly, the actual length of the artery was calculated by summing the incremental distances between each of the centroid, and geometric length was calculated between the start and end points of the volume. Tortuosity values were calculated by dividing the actual length by the geometric length.

## Results

The script was mainly developed using a single artery's data, but toward the end of the study it was applied to nine others. This revealed some bugs and inconsistencies of several parts of the code, since the results were shaky for a few arteries. Overall though, results were generally decent, as shown in the Fig. 4 below (the figures included in this section only show best and worst case results). The orange cloud of points represents the artery volume; the green lines represent data relevant for debugging and showing intermediate steps. The pink dots show the final centroids.

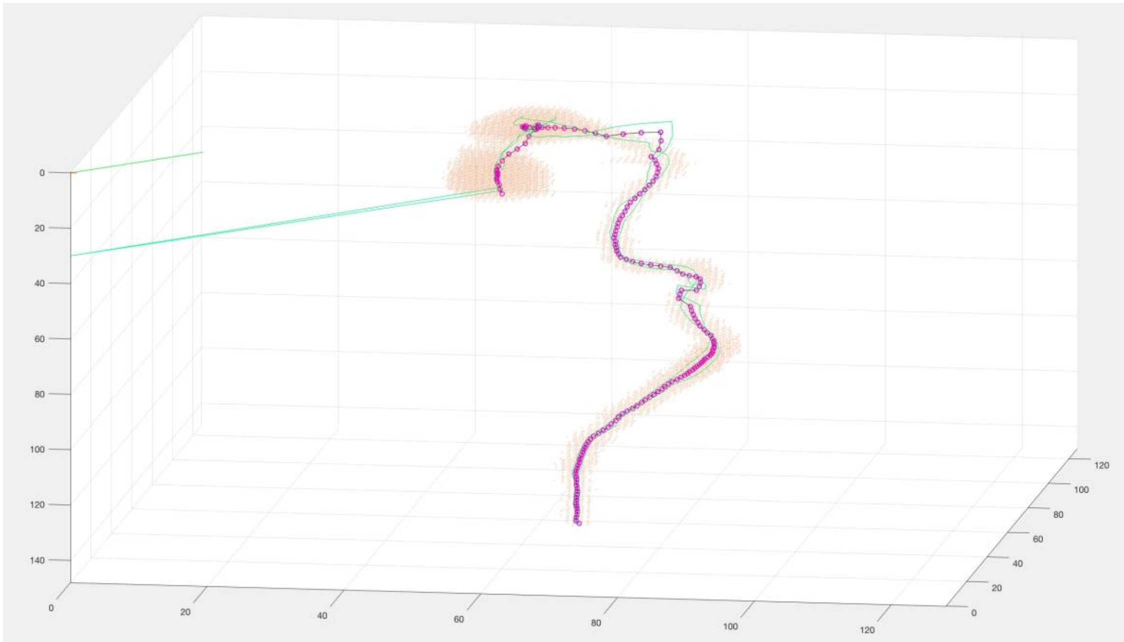

**Fig. 3 Artery from 2-month-old mouse #1 of cage 15392, example of imprecisions in the code**

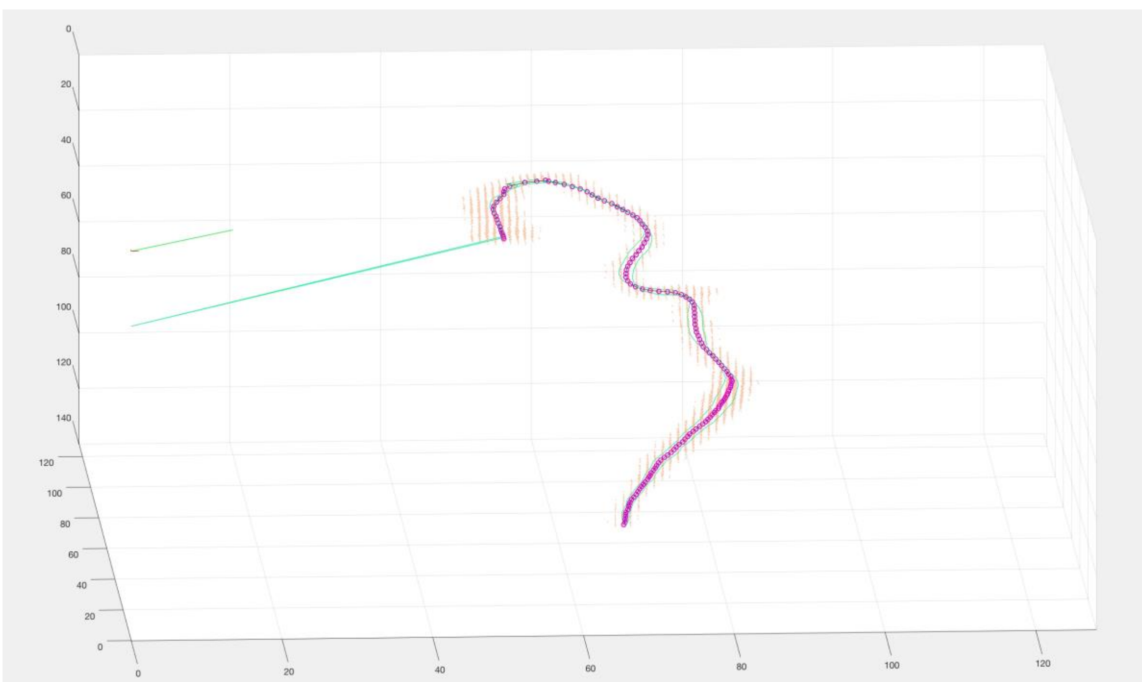

**Fig. 4 Artery of 2-month-old mouse #3, cage 15474, exemplary script accuracy despite challenges**

Table 1 below shows the calculated lengths and tortuosity values for the ten mice. The red rows correspond to measurements that seemed highly distorted on the graphical rendition of the artery, orange rows show slightly distorted values, and green rows represent satisfying values.

**Table 1 Tortuosity and actual lengths for 2-month old mice (Cage#_Mouse#)**

| Mouse (All Fbln4_sm22Cre) | Month 2 Tortuosity | Month 2 Length |
|---|---|---|
| 15392_1 | 3.17 | 378.5 |
| 15392_2 | 2.21 | 295.2 |
| 15398_1 | 2.01 | 242.8 |
| 15398_3 | 2.31 | 269.7 |
| 15466_1 | 2.63 | 295.4 |
| 15466_3 | 2.68 | 309.4 |
| 15469_3 | 2.59 | 303.9 |
| 15474_2 | 2.08 | 227.8 |
| 15474_3 | 2.03 | 235 |
| 15389_1 | 1.72 | 205.9 |

## Discussion

Table 1 quickly shows that the MATLAB script written is reliable for approximately 60% of the arteries it encounters. Multiple elements contribute to the imprecisions, as shown in Fig. 3. First, one can see the low resolution of the initial data leads to choke points on the artery, which mess up the procedure of the code and lead to unexpected results. Second, the geometry of the arch combined with the current smoothing method can lead to finding centroid values that don't fall inside the actual artery, as displayed by the triangular protrusion near the top. Lastly, if the arch is wider than average, one can obtain disordered centroid values, which increases tortuosity by adding back and forth lengths to the calculations (this is shown by the jumble of points at the top).

On the other hand, the script worked better than anticipated for several arteries. Figure 4 shows the ideal capabilities of the code, with the centroid calculation navigating sharp angles and thin areas with finesse. Rotating the corresponding model shows that the centroids are convincingly plotted in the middle of the artery from all angles, and calculated tortuosity values are amongst the lowest calculated despite the apparent tortuosity (this suggests high efficiency and few noise related distance increases throughout the process).

Toward the end of the study, it was discovered that the z-axis coordinates found for all points were compressively distorted, since the x-axis and y-axis resolution of the MRI images were twice as high as the z-axis picture spacing. This means that the actual figures should be more stretched out than they currently are. Consequentially, the tortuosity values reported are all off (including the green shaded values). This is better news than one might think, since rendering the properly spaced points should smooth out some higher curvature regions that are currently problematic for the code. Whereas many tortuosity values currently found are close to 2, they will get closer to 1.5 or so after this main issue is addressed.

## Conclusion

As the MATLAB script currently functions, it could be used to acquire significant data for about half of the arteries it's applied to. Graphical observation is still necessary to gauge confidence in results for each case (how accurate do the centroids look from all angles), and will continue to be used to improve the code during summer research. As current issues are addressed and as more issues are discovered through application of the script to new data, the accuracy of the script will be improved until deemed reliable. Results will also be compared to alternative means of calculating tortuosity provided by other lab members. The script should soon be ready to yield solid results that can be used to further the study of links between tortuosity and CTDs, and could be easily modified to yield diameter values along the arteries. With more considerable effort, the script could be modified to yield analysis of curvature along the volume, including a count of the number of curvature direction inversions that take place in the artery.

**References**

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